TOC E149-61
October 5, 1961

RJA 2/26/62

AD610258

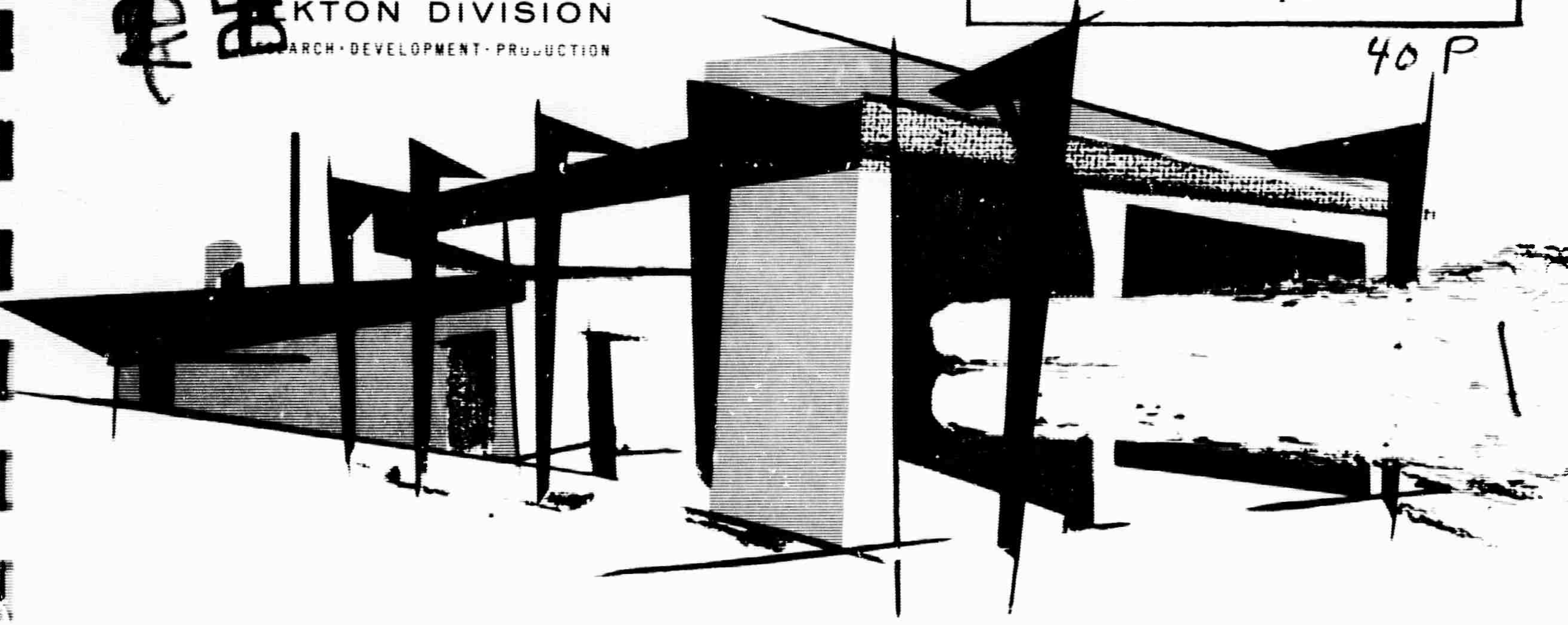
DDC
RECEIVED
JAN
DDC-IRA B

~~DDC FILE COPY~~

COPY 1 OF 1	R
HARD COPY	$. 2.00
MICROFICHE	$. 0.50

40 P

Thiokol®
KTON DIVISION
ARCH·DEVELOPMENT·PRODUCTION



QUARTERLY TECHNICAL REPORT NUMBER 1 - MAY 15, 1961 THROUGH AUGUST 15, 1961 - EXPERIMENTS FOR THE MEASUREMENT OF THE ACOUSTIC IMPEDANCE OF A BURNING SOLID PROPELLANT

PROCESSING COPY
ARCHIVE COPY

6731

ARPA Cont. No.

FIPC File Cy

AD 610258

E149-61

THIOKOL CHEMICAL CORPORATION
ELKTON DIVISION
ELKTON, MARYLAND

QUARTERLY TECHNICAL REPORT NUMBER 1

MAY 15, 1961 THROUGH AUGUST 15, 1961

EXPERIMENTS FOR THE MEASUREMENT OF THE ACOUSTIC IMPEDANCE OF A BURNING SOLID PROPELLANT

CONTRACT NUMBER NONR 3473(00)

ARPA ORDER NUMBER 23-61

OCTOBER 5, 1961

H. G. Jones

H. G. Jones
General Manager

FOREWORD

This quarterly report has been prepared by the Elkton Division of Thiokol Chemical Corporation and describes the initiation of effort on a program to develop instrumentation and measure the acoustic impedance of a burning solid propellant.

The studies have been conducted in the research laboratories located at Elkton, Maryland. Contributors to this report are:

E. S. Stern, Principal Investigator, Research Section

J. R. Woodyard, Physicist, Research Section

Dr. A. O. Converse, Program Consultant, Carnegie Institute of Technology

The studies have been conducted under the general supervision of Dr. G. R. Leader, Head, Physical and Analytical Chemistry Group and Dr. C. C. Alfieri, Head, Research Section. The Program Manager is M. D. Rosenberg.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

This report describes the progress made during the first quarter of this research program to measure the acoustic impedance of a burning solid propellant. Equipment needed to conduct experiments designed to yield information about the mechanism and conditions of combustion instability has been fabricated.

Equations have been used to establish the desired boundary conditions and to serve as a basis for further investigations. The limitations and assumptions used in deriving these equations are discussed.

Results of preliminary experiments using this apparatus are presented.

I. INTRODUCTION

During the development of solid rocket propellant motors, the problem of unstable or oscillatory burning is occasionally encountered. In practice, unstable burning may cause a variety of malfunctions in the rocket motor, the most serious, of course, being complete failure of the propulsion system. Additional penalties which may be incurred when unstable burning is encountered are undesirable modification of motor hardware and serious time delays in the development of critically needed military weapons and space exploration vehicles.

Presently there is no adequate theory that enables the designer to predict the magnitude of the ballistic parameters when unstable burning occurs. The designer must rely on experience and the data accumulated from past rocket motor development programs.

This study, being pursued under contract No. Nonr 3473(00), ARPA Order No. 23-61, is the first phase of a program for measuring the acoustic impedance of a burning solid propellant. Its objective is the evaluation of the feasibility of using a modification of the method developed by O.K. Mawardi[16] for the measurement of the impedance of inert materials (passive tests). This technique will be considered feasible for this program if it can be shown that burning propellant acts as an amplifier for acoustic energy (active tests).

The study consists of four parts:

1. The building of the apparatus.
2. Determination of the frequency spectrum of the combustion noise.

3. Determination of the acoustical characteristics of the apparatus without burning propellant.

4. Measurement of the qualitative effect of burning propellant surface on sound over a range of frequencies.

If it can be successfully demonstrated that burning propellant acts as an amplifier, further studies can be conducted to make the measurement quantitative so that the results can ultimately be used to aid in designing stable operating, solid rocket motors more efficiently.

Recent observations of oscillatory combustion[1,2,3] have indicated that the burning rate response is dependent on the acoustic environment at a given point on the burning surface. During unstable performance, the gas oscillations occur in characteristic modes of the combustion chamber[4], implying that the acoustic environment varies as a function of the cavity and is therefore related to the location on the propellant burning surface.

Recent theoretical investigations on the mechanism for the coupling of pressure variations with the propellant combustion process have been reported[5,6,7,8,9,10]. In a solid propellant rocket motor, the acoustic instability is a balance of the acoustic gains and losses in the system[11]. One mechanism for energy gain can occur within the thin burning zone, which is capable of amplifying pressure disturbances at the surface[12,13] thereby causing self sustained oscillations to occur when this gain balances the cavity losses. Thus, in a given cavity the tendency to oscillate is most probable when a mode has an acoustic pressure maximum at the surface.

Existing theoretical work has shown the importance of the burning propellant boundary condition (or acoustic impedance) but previous experimental work has not been focused on this point before submission of the program[14] on which this study is based.

II. BACKGROUND

Previous experimental work on unstable combustion can be divided into two categories: first, the investigation of propellant composition and motor design changes to eliminate unstable burning in motors where it has occurred; and second, attempts to reproduce the phenomenon in the laboratory. A summary of recent work[14] is given in Table I. This summary indicates that no attempt has been made to determine the relationship between pressure and velocity at the propellant surface. This relationship forms the mathematical boundary condition which is the essence of the problem. A summary of theoretical studies is presented in Table II. These studies are concerned with the boundary condition at the burning propellant surface. Treatment of this boundary condition appears to be the main point of disagreement among the several theories proposed by various researchers.

At a technical panel meeting[15] held in March 1961, four laboratory methods for measuring the acoustic impedance of the burning surface of a solid propellant were presented: the shock tube, the transmission line, the Helmholtz resonator, and this investigation - namely, the modification of Mawardi's method[16].

TABLE I

UNSTABLE BURNING - RECENT EXPERIMENTAL STUDIES

Investigator	Location	Object of Work	Reference
L. Watermeir	Aberdeen Proving Ground Ballistics Research Lab.	1. Reproduction of D.C.* Effects in Laboratory	BFL Memo. Report No. 1172 October 1958
		2. Analysis by high speed motion pictures	personal visit
Brettschneider	Thiokol Chemical Corp. Redstone, Alabama	1. Reproduction of D.C.* Effects	JANAF Meeting June 1959, p291 Vol IV
Lou, Cheung	Aerojet-General Corporation Sacramento, California	1. Investigate the mechanism of unstable burning	JANAF Meeting June 1959, p 233, Vol IV
		2. Test suppressants in motor firings	
Waesche	Rohm and Haas Company Redstone, Alabama	1. Investigation of mechanism and means of suppressing unstable burning	JANAF Meeting June 1959 p [illegible]71, Vol IV
Price	NOTS China Lake, California	1. Evaluation of suppressants by reproducing unstable burning in small test motors	Tech. Prog. Reports 211 and 218
		2. Evaluation of mechanisms, velocity vs. pressure	
		3. Reproduction of D.C.* effect	
Angelus	A. B. L.	1. Evaluating the effect of the fit between grain and case by motor firings.	Letter: McClure to Gibson

* Unstable burning in which the mean chamber pressure is altered.

TABLE II

UNSTABLE BURNING-SUMMARY OF THEORETICAL STUDIES

Investigator	Year	Part of Problem Covered					Assumptions with Regard to Time Process		Reference
		Burning Propellant Boundary	D. C. Effects	A. C. Problem including Boundaries	Damping Action of gas Phase		Assumes time lag	Uses time dependent equations	
Grad	1949	X					a const.		17
Smith and Springer	1953	X						Qualitative	18
Cheng	1954	X		X			a function of pressure		19
Moore - Paslen	1954	X					Both		20
Aeroneutronic					X				21
Green	1958-59	X	X				X		5
McClure & Hart	1958-60	X	X					X	6

III. THEORY

The pressure-time traces from solid propellant rocket motors which exhibit unstable operation show that two phenomena are present. The primary phenomenon is a pressure oscillation having a frequency corresponding to an acoustic mode. The second phenomenon, a change in the mean pressure, results from the first phenomenon through an increase in burning rate. These phenomena are referred to as A.C. and D.C. effects, respectively.

The problem of unstable combustion in a rocket motor can be considered to be the same as the problem of acoustic waves in a gas filled cavity, with rather unusual boundary conditions. Cheng[19] treated the problem in this manner, using the rather artificial boundary condition of a centrally-perforated case-bonded grain.

The required boundary conditions are the ratios of the instantaneous sound pressure to the instantaneous velocities at the boundaries of the gas cavity in the rocket motor. This ratio is defined as the specific acoustic impedance,

$$Z = p/\mu$$

The boundaries at which the pressure-velocity relationship must be known to make use of this method are indicated in Figure 1. The conditions at the nozzle have been treated approximately by Crocco[23]. As was stated previously, the boundary condition (impedance) at the burning-propellant surface is unknown. Attempts to calculate this value have been prevented by lack of information of the kinetics of the reaction and by the complexity of the problem. McClure and Hart[6] selected the heat and mass transfer processes, depicted below in Figure 2, as the slowest and, therefore, most important from an order-of-magnitude estimate of the speed of the various transport and chemical processes.

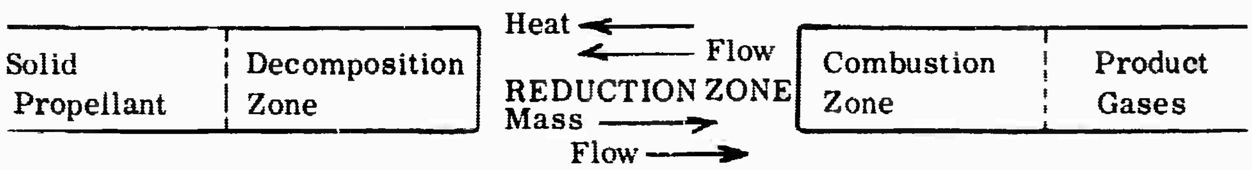


FIGURE 2. HEAT AND MASS TRANSFER PROCESSES

McClure and Hart[6] find that the impedance is a function of 17 variables for a rigid, homogeneous propellant. Applying their treatment to the viscoelasticity and inhomogeneity of the composite propellants increases the complexity of the problem. The impedance as expressed by Cheng[19] appears much simpler. It would, however, require a study of the chemical kinetics to verify it. It is, therefore, easier to determine the impedance experimentally than to calculate it. It should be noted that theoretical calculations require data that must be obtained from extremely complicated experiments.

A-00635

U_x = AXIAL VELOCITY

U_r = RADIAL VELOCITY

U_o = CIRCUMFERENTIAL VELOCITY

P = PRESSURE

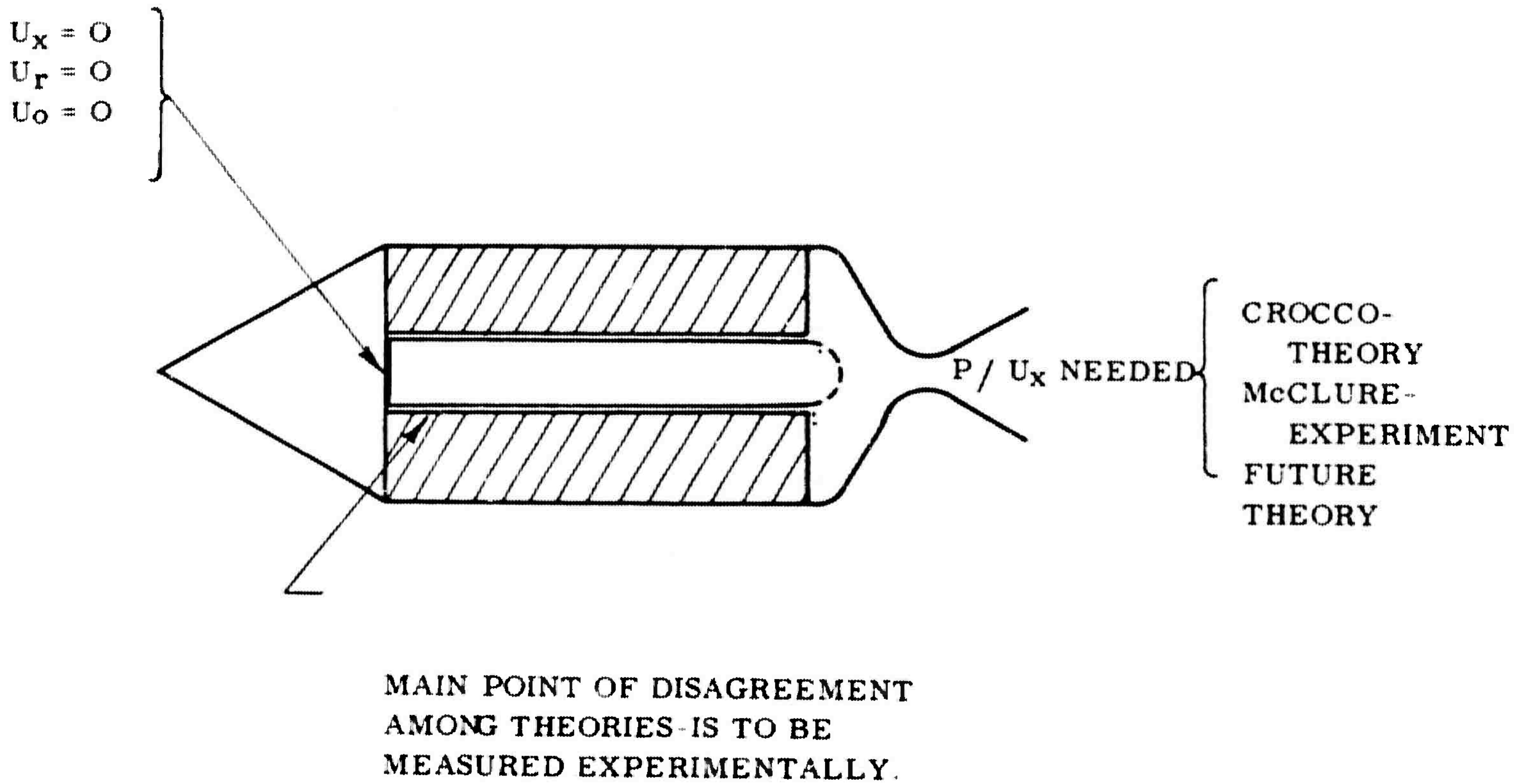


FIGURE 1. BOUNDARY CONDITIONS

IV. EXPERIMENTAL METHOD

Following a thorough review of several methods of measuring the acoustic impedance[24], the technique developed by O. K. Mawardi[16] was selected as the experimental approach to the problem. This approach satisfies the requirement that the measurement be made quickly, before the propellant burns out. Combustion products and heat can be removed by modifying the apparatus. Its suitability when a heat and mass source is present will have to be determined in this program.

A sketch of the apparatus is presented in Figure 3. The operation of this apparatus is more easily understood by referring first to Figure 4.

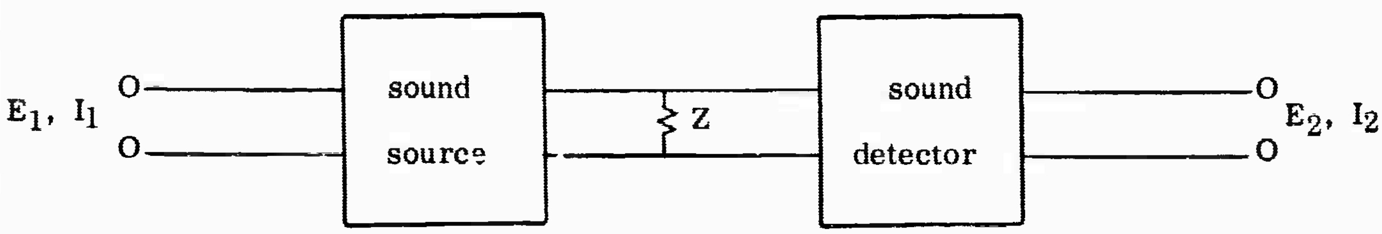
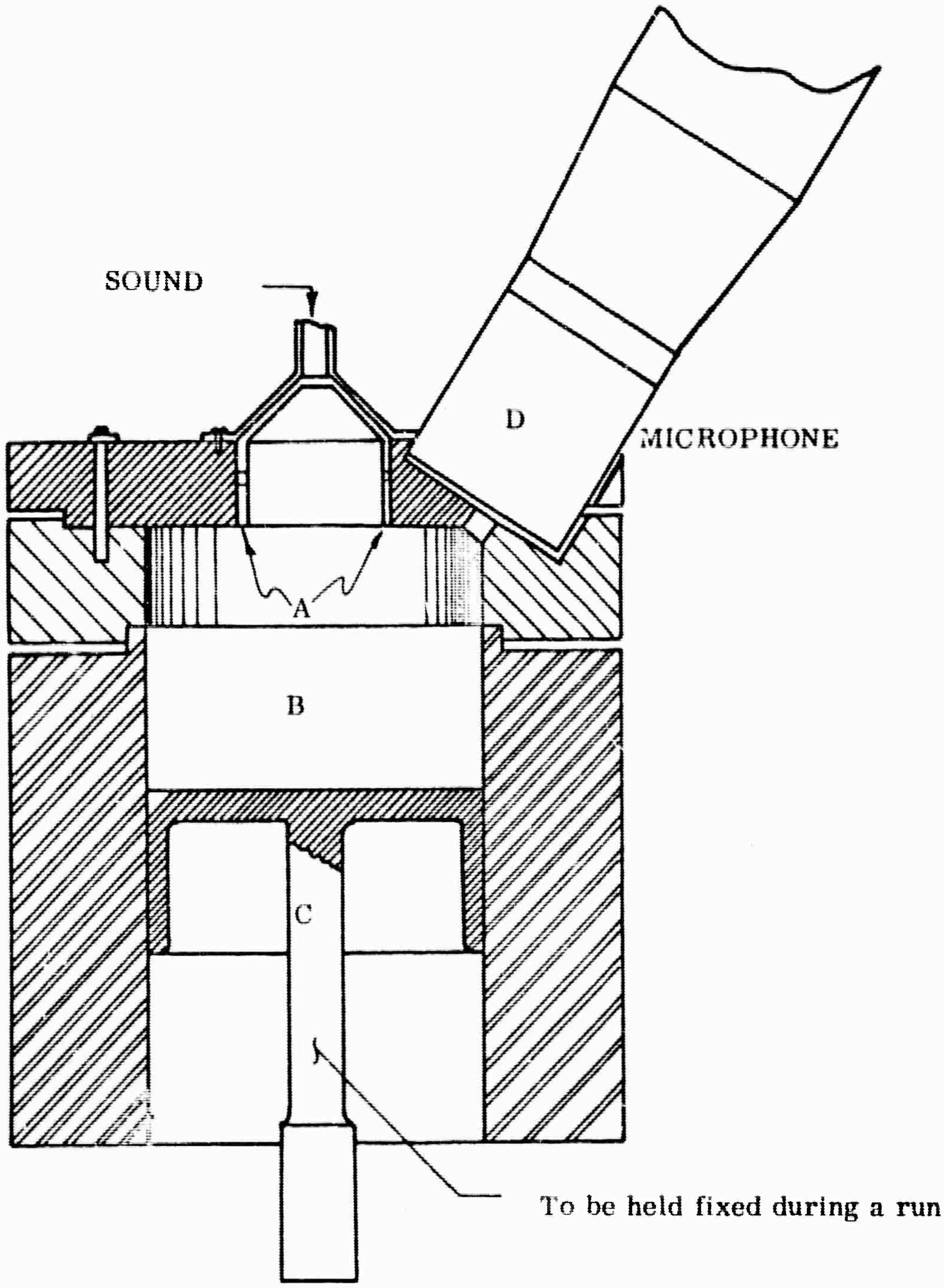


FIGURE 4. SCHEMATIC DIAGRAM OF APPARATUS TO DETERMINE ACOUSTIC IMPEDANCE

As shown in Figure 4, the apparatus consists of an electrically driven sound source connected to a detector through the impedance Z of the chamber; or the impedance of the chamber plus an unknown impedance produced by a sample. The input current I_1 and voltage E_1 to the source and the output current I_2 and voltage E_2 from the detector are directly measurable.



$$Zm = Z_1 \left[1/(E_1/E_2 - 1)\right]$$

Zm = IMPEDANCE OF THE PROPELLANT

Z_1 IMPEDANCE OF THE CHAMBER

E_1 VOLTAGE FROM PRESSURE PICKUP WITHOUT PROPELLANT

E_2 VOLTAGE FROM PRESSURE PICKUP WITH PROPELLANT

FIGURE 3. APPARATUS TO DETERMINE ACOUSTICAL IMPEDANCE (AFTER MAWARDI)

For a system which can be considered a lumped impedance, a simple relationship, $P = IZ$, exists, where:

P = pressure developed in the chamber

I = volume current in the chamber

Z = impedance of the system.

A volume current is injected into the chamber with rigid walls and the pressure, $P_1 = IZ_1$, is noted where:

$$\frac{1}{Z_1} = \frac{1}{Z_c} + \frac{1}{Z_o}$$

Z_c = impedance of the chamber air volume

Z_o = input impedance of source and detector.

The procedure is repeated with one of the walls lined with the sample material whose impedance Z_m is to be determined. A new pressure $P_2 = IZ_2$ results, where:

$$\frac{1}{Z_2} = \frac{1}{Z_c} + \frac{1}{Z_o} + \frac{1}{Z_m}$$

If the system is linear and E_2' and E_2'' are the corresponding outputs from the detector for a constant input current I, the expressions reduce :

$$Z_m = Z_c \left[\frac{1}{\frac{E_2'}{E_2''} - 1} \right] \left[\frac{1}{1 + \frac{Z_c}{Z_o}} \right] \tag{1}$$

Where:

E_2' - voltage from microphone without sample

E_2'' - voltage from microphone with sample

Z_c - impedance of chamber without unknown, $(\gamma P)/j\,W\,V)$

Z_o - parallel combination of the input impedances of source and detector.

Constructing the apparatus so that $Z_c/Z_o \ll 1$, equation (1) reduces to

$$Z_m = Z_c \left[\frac{1}{\frac{E_2'}{E_2''} - 1} \right] \tag{2}$$

Since Z_1 can be calculated and E_2' and E_2'' measured, Z_m can be determined. For the active tests, the unknown is burning propellant and it is assumed that these same equations apply.

The outputs E_2' and E_2'' are measured both in magnitude and phase. The phase angle is referred to the input current I_1, which is maintained constant throughout the experiment. Therefore,

$$\frac{E_2'}{E_2''} = \frac{|E_2'|}{|E_2''|} \frac{e^{j\phi_1}}{e^{j\phi_2}} = \beta e^{j\phi}$$

substituting in expression (2)

$$Z_m = Z_c \ (1/\beta e^{j\phi} - 1)$$

Analysis shows that the pressure distribution inside the cavity is uniform for a ring source. Since the pressure distribution is uniform, the enclosure may be represented by a lumped impedance Z. The analysis is being experimentally verified.

Linearity means that for every element in the system, the response is proportional to the excitation. This is a property which must be 'built in' the system and experimentally demonstrated. This property is also being experimentally verified.

A. Relationship Between Impedance and Amplification

Morse[25] shows that the ratio between the reflected and incident energy (i.e., the rate at which energy is transmitted along a wave) for normal incidence is

$$\left|\frac{P_r}{P_i}\right|^2 = \left|\frac{1 - \frac{Z}{\rho c}}{1 + \frac{Z}{\rho c}}\right|^2$$

For amplification,

$$\left|\frac{P_r}{P_i}\right|^2 > 1$$

Let $Z = R + j X$, then have

$$\left|\frac{1 - \frac{R}{\rho c} - j\frac{X}{\rho c}}{1 + \frac{R}{\rho c} + j\frac{X}{\rho c}}\right|^2 > 1$$

$$(\rho c - R)^2 + X^2 > (\rho c + R)^2 + X^2$$

$$\therefore \; -R > R, \text{ i.e. } R < 0$$

The necessary and sufficient condition for amplification is that the real part of the acoustic impedance be negative.

B. Significance of the Phase Angle ϕ

The following expressions from lumped acoustic impedance theory are valid for the frequency ranges to be investigated.

$$Z_c = \frac{-\gamma P j}{2\pi f V} \; ; \quad Z_m = Z_1 (\beta e^{j\phi} - 1) \quad \text{where} \quad \beta e^{j\phi} = \left| \frac{E'_2}{E''_2} \right| e^{j(\phi_1 - \phi_2)}$$

Let $Z_m = R + jX$

$$Z_m = \left[\frac{-\gamma P j}{2\pi f V} \right] \cdot \left[\frac{1}{\beta e^{j\phi} - 1} \right]$$

$$Z_m = \left[\frac{-\gamma P j}{2\pi f V} \right] \cdot \left[\frac{1}{\beta \cos \phi - 1 + j \beta \sin \phi} \right]$$

$$Z_m = \left[\frac{-\gamma P j}{2\pi f V} \right] \cdot \left[\frac{\beta \sin \phi + j (\beta \cos \phi - 1)}{(\beta \cos \phi - 1)^2 + (\beta \sin \phi)^2} \right]$$

$$R = \left[\frac{-\gamma P}{2\pi f V} \right] \cdot \left[\frac{\beta \sin \phi}{(\beta \cos \phi - 1)^2 + (\beta \sin \phi)^2} \right]$$

$$X = \left[\frac{-\gamma P}{2\pi f V} \right] \cdot \left[\frac{\beta \cos \phi - 1}{(\beta \cos \phi - 1)^2 + (\beta \sin \phi)^2} \right]$$

It has been established that for $Z = R + jX$, R is negative when amplification occurs at the surface being considered. From the expression for R it can be concluded that R is negative only if $\sin \phi$ is positive, i.e., $0 < \phi < \pi$.

As a result of this analysis, the feasibility of a modified Mawardi's method can be determined while the experiment is in progress. This will be done by using a phase meter with a recorder.

C. Established Criteria

1. Both amplitude and phase measurement are necessary for determination of impedance.

2. Amplification occurs when the real part of the impedance is negative.

3. The real part of the impedance is negative only if the phase angle ϕ is $0 < \phi < \pi$.

V. DESCRIPTION OF APPARATUS

A. Sound Chamber

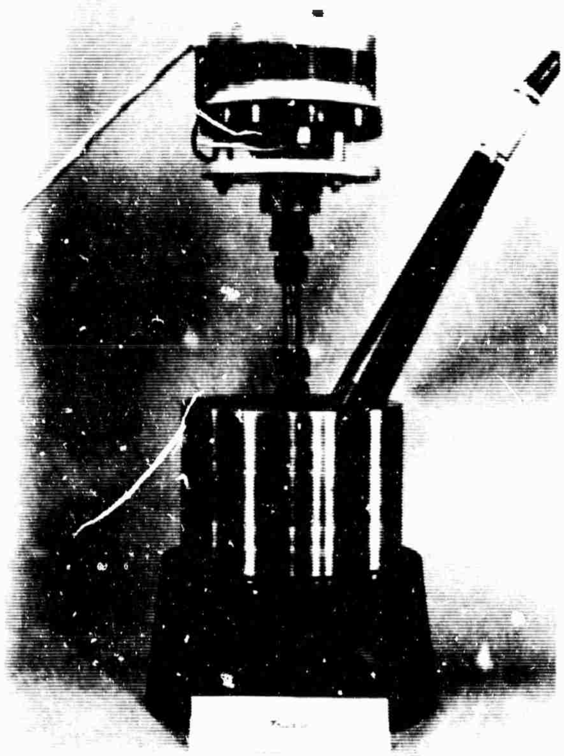
The sound chamber assembly with the driver and microphone used for initial testing is shown in Figure 5. This sound chamber is capable of accepting a two inch diameter by one-half inch thick sample.

The sound chamber itself (Figures 6 and 7) consists of: (a) a head plate to which the driver unit, ring source and microphone pick-up are attached, (b) an interchangeable body having a cylindrical cavity (bodies have lengths of 0.697 inch, 1.098 inches, and 2.296 inches), and (c) a base plate. To prevent pressure leaks, O-ring seals are used between components. The head plate is aligned with the body by dowel pins and the assembly is held rigid with three cap screws.

The sound from the driver is transmitted through a copper wire filled tube (1/4 inch I.D) to the ring source. The ring source is an integral part of the head plate and is realized by suspending a spool within the head. Alignment is maintained by positioning the spool with centering pegs. The annular opening (0.027 inches) is also packed with copper wire. The clearance is such that sound is afforded a continuous passage.

The pressure detector, a dyamic microphone, is attached to the head plate in such a manner that the end of the probe is flush with the inner face.

Care must be taken to insure airtight joints since leakage would introduce serious errors in the measurements. Massive construction was employed as cavities with thin walls could easily be affected by extraneous noise.

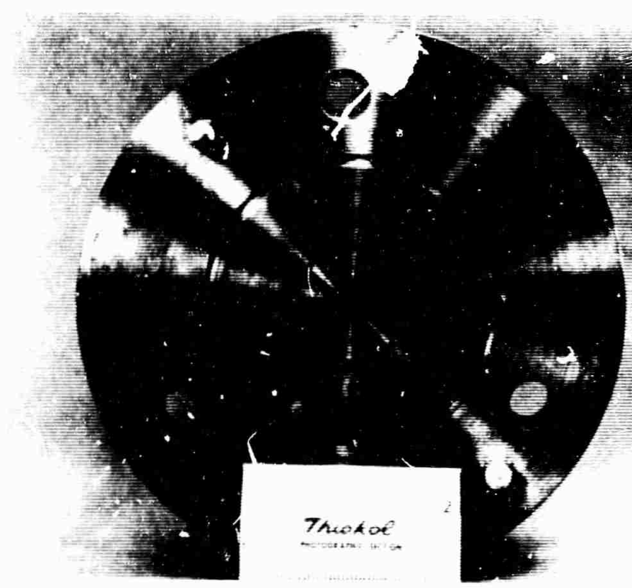


761144

FIGURE 5. SOUND CHAMBER WITH DRIVER AND MICROPHONE

761145

FIGURE 6. (LEFT TO RIGHT). HEAD PLATE, BODY, SAMPLE DISC AND BASE OF SOUND CHAMBER.



761146

FIGURE 7. HEAD PLATE CLOSE-UP SHOWING ANNULAR OPENING FOR SOURCE, PROBE TUBE FOR MICROPHONE, "O" RING GROOVE AND DOWEL PINS.

B. Electrical

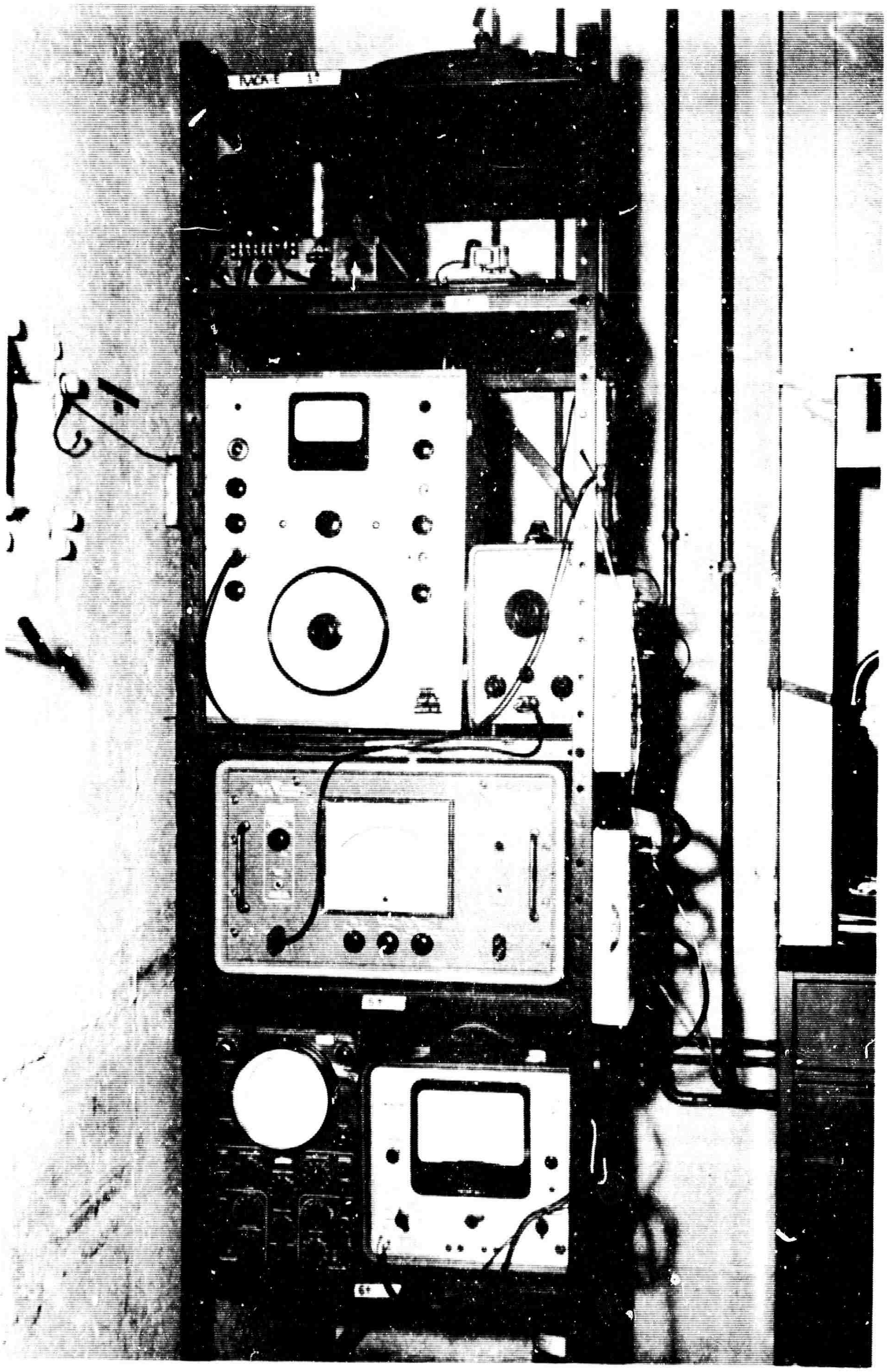
A photograph showing the general appearance of the electronic instrumentation is presented in Figure 8. A block diagram of the passive experimental instrumentation is shown in Figure 9. The amplifiers for the driver unit and the microphone are of conventional type, exhibiting excellent frequency response and low hum level.

The essential components of the instrumentation that are now being used are listed below.

Ad-Yu Electronics, Phase Meter, Type 405
Bruel and Kjaer, Audio Frequency Spectrometer, Model 2111
Bruel and Kjaer, Condenser Microphone, Type 4134
Bruel and Kjaer, Probe Microphone Kit, Type VA 0040
Bruel and Kjaer, Cathode Follower, Type 2615
Precision, Voltmeter, Model 98 MCP
Hewlett-Packard, Audio Oscillator, No. 201C
McIntosh, Amplifier, Type MC-60
Electronic Measurements Company, Voltage Regulator, Model 260 AM

C. Procedure

With the apparatus connected as shown in the block diagram (Figure 9) the oscillator and amplifier voltages are set with the oscillator turned to 1000 c/s. E_2' and ϕ are recorded as a function of frequency with the rigid termination. The sample whose impedance Z_m is to be determined is inserted as the termination. E_2'' and ϕ_2 are recorded. The quantitative value of Z_m is obtained by referring to the bipolar chart and multiplying the solutions of the inversion of the vector $\beta e^{j\phi}-1$ by Dj, when D is a constant whose values depend on the length of the chamber body and the correction factors[27].



861249 FIGURE 8. INSTRUMENTATION FOR THE MEASUREMENT OF THE ACOUSTIC IMPEDANCE OF A BURNING SOLID PROPELLANT

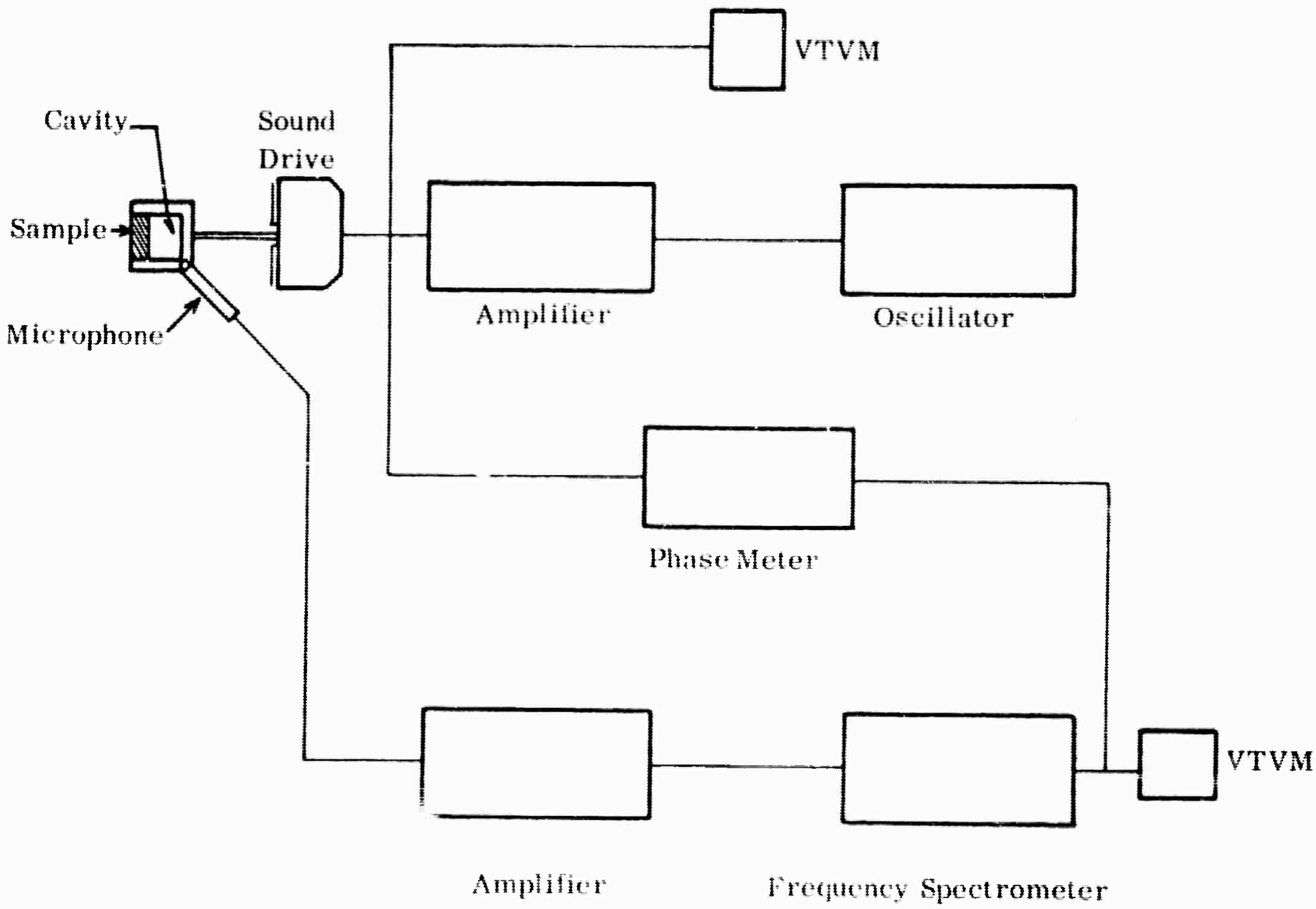


FIGURE 9. BLOCK DIAGRAM OF PASSIVE EXPERIMENTAL INSTRUMENTATION

VI. PASSIVE TESTS

In order to obtain familiarity with the operating techniques and problems, equipment was assembled so that Mawardi's experiment could be duplicated. In this preliminary phase, it was anticipated that a similar test specimen could be used to 'calibrate' the sound chamber. However, the sample material used by Mawardi, a Celotex C-4, is no longer being manufactured.

Several passive tests were conducted with acoustical materials. The measured impedance values were essentially in agreement with those reported in the literature. A comparison of data for samples of Johns Manville 'Airacoustic' with results reported by L. L. Beranek is shown in Figure 10. The observed differences are believed to be due to the low acoustic impedance microphone that was used. Another cause for the differences observed is the thickness of sample used; Beranek used a one inch thick sample while, for this investigation, a one-half inch thick sample was used. A high acoustic impedance microphone (Bruel and Kjaer, condenser microphone, type 4134) has been integrated into the instrumentation and it is anticipated that results in closer agreement with Beranek's will be obtained in subsequent tests.

Samples of materials tested in our sound chamber are being sent to T. A. Angelus at Allegany Ballistic Laboratory to determine impedance values using a standing wave apparatus. This independent check on our results by a different technique will strengthen the confidence in the Elkton method and experimental technique.

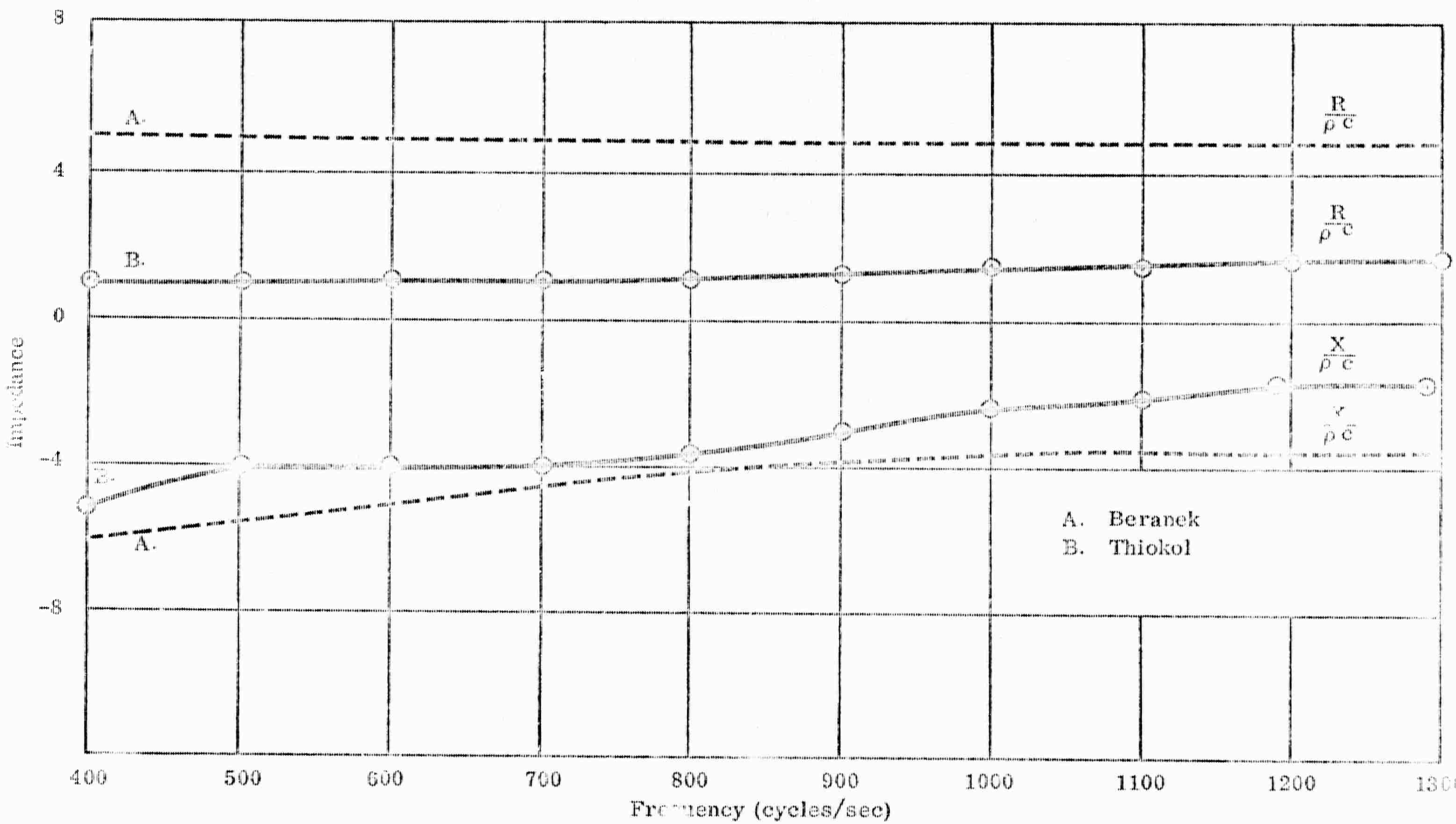


FIGURE 10. IMPEDANCE AS A FUNCTION OF FREQUENCY FOR JOHNS-MANVILLE 'AIRACOUSTIC', SPECIFIC IMPEDANCE, $z = \frac{R}{\rho c} + j\left(\frac{X}{\rho c}\right)$.

Under the auspices of the American Society for Testing Materials, Committee C-20 conducted a 'round robin' series of impedance tube tests in 1952. The test program involved the measuring of the acoustical properties of materials by several laboratories. We have requested samples of the materials used and the results of the 'round robin' tests from the Celotex Research Laboratory.

To reduce the tedious computation time required to obtain the impedance values from the raw experimental data, a bipolar chart has been constructed. With this chart, impedance values can be obtained immediately by referring to the parametric curves which are expressed in terms of the data. In constructing the bipolar chart, values were programmed on an IBM-650 and the computer output fed to a Benson-Lehner electroplotter.

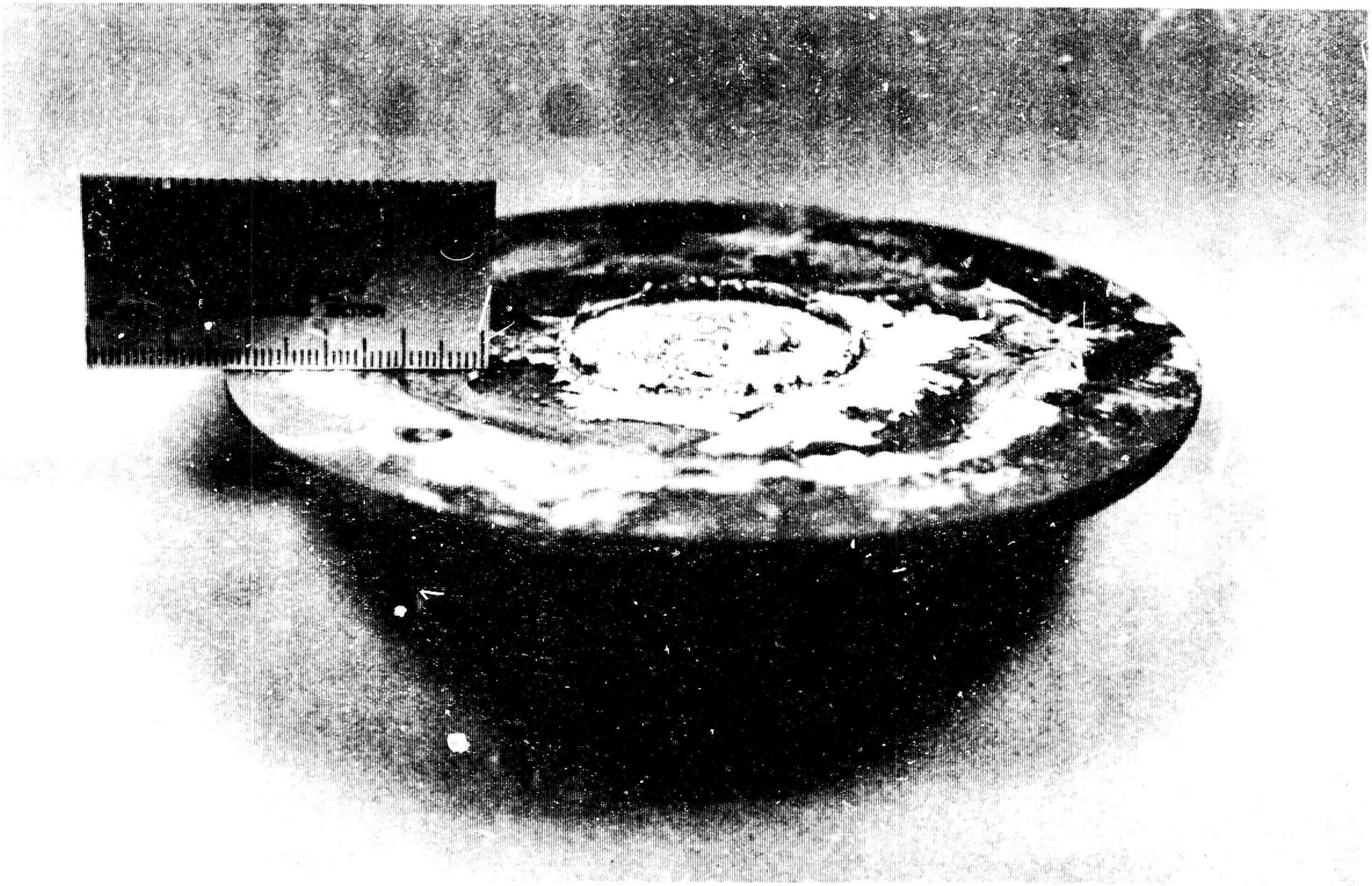
VII. ACTIVE TESTS

For initial tests it would be desirable for the propellant selected to have the following characteristics: low burning rate; instability history at low frequency; and a clean exhaust. A survey of propellants possessing these properties was undertaken. Using information obtained during previous rocket motor development programs, several candidate formulations were selected for further consideration. These include polysulfide formulations T-17E2, TRX-135, and T-22, and urethane formulation TP-G-3013A, each of which has evidenced varying degrees of combustion instability when used in motors having specific geometries conducive to such instability. The urethane formulation and its possible modifications currently appear to offer the most desirable combination of desired properties.

An uninstrumented model of an active sound chamber having the same internal dimensions as the passive chamber was constructed and samples of highly aluminized and non-aluminized propellants were fired. From these preliminary tests, qualitative information was obtained on the temperature gradients in the chamber, deposition of condensed particles on the chamber walls, ease of sample ignition and pressure shock due to ignition. Photographs of the chamber after tests conducted with aluminized and non-aluminized propellants are shown in Figures 11 to 15. As might be anticipated, the relative condensed particle build-up on the chamber walls was greater when propellants containing aluminium were fired. (Compare Figure 11 with Figure 14 and note blockage of port). Tempilac, a temperature sensitive paint, was applied to the chamber before firing and indications of the temperature gradient were obtained by examination of the Tempilac-coated metal parts after each test.

Mathematical determination of the gas flow criteria for the system, pressure build-up, consideration of ignition characteristics, and perforated plate sizing will be accomplished in conjunction with the selection of a preliminary sample propellant.

861207 FIGURE 11. PARTICLE DEPOSITION ON CHAMBER WALLS - ALUMINIZED PROPELLANT



861208 FIGURE 12. PARTICLE DEPOSITION ON CHAMBER WALLS - ALUMINIZED PROPELLANT

861209 FIGURE 13. PARTICLE DEPOSITION ON CHAMBER WALLS - ALUMINIZED PROPELLANT

961084 FIGURE 14. PARTICLE DEPOSITION ON CHAMBER WALLS - NON-ALUMINIZED PROPELLANT

961085 FIGURE 15. PARTICLE DEPOSITION ON CHAMBER WALLS
NON-ALUMINIZED PROPELLANT

NOMENCLATURE AND KEY TO SYMBOLS

Z	=	acoustic impedance
Z_1	=	impedance of chamber air volume, $(\gamma P)/(j\omega V)$
Z_o	=	parallel combination of the input impedances of source and detector
Z_m	=	impedance of sample
P	=	amplitude of static pressure
P_r	=	amplitude of reflected pressure wave
P_i	=	amplitude of incident pressure wave
p	=	instantaneous sound pressure
ϕ_1	=	microphone voltage phase angle with rigid termination reference to driver voltage phase angle
ϕ_2	=	microphone voltage phase angle with sample termination reference to driver voltage phase angle
ϕ	=	$\phi_1 - \phi_2$
c	=	speed of sound
ρ	=	density of gas
μ	=	particle velocity
ω	=	angular frequency, $2\pi f$
V	=	volume of the cavity
γ	=	ratio of specific heats
E_2'	=	voltage from microphone with rigid termination

E_2'' = voltage from microphone with sample termination

j = $\sqrt{-1}$

f = frequency

A = area of sample surface

ρc = characteristic impedance of gas in chamber

R = resistive part of impedance, real part of Z

X = reactive part of impedance, imaginary part of Z

L = chamber length

β = $\left| \dfrac{E_2'}{E_2''} \right|$.

REFERENCES

1 Price, E. W., 'Combustion Instability in Solid Propellant Rocket Motors', ARS Journal, Vol. 30, No. 6, June 1960, pp. 574-576.

2 Crump, J. E. and Price, E. W., 'Catastrophic Changes in Burning Rate of Solid Propellants During Combustion Instability', ARS Journal, Vol. 30, No. 7, July 1960, pp. 705-707.

3 Price, E. W., and Safferis, J. W., 'Combustion Instability in Solid Propellant Rocket Motors', Jet Propulsion, Vol. 28, No. 3, March 1958, pp. 190-192.

4 Crump, J. E., and Price, E. W., 'Effect of Acoustic Environment on the Burning Rate of Double-Base Solid Propellants', ARS Journal, July 1961.

5 Green, L., Jr., 'Some Properties of a Simplified Model of Solid Propellant Burning', Jet Propulsion, Vol. 28, 1958, p. 386.

6 Hart, R. W., and McClure, F. T., 'Combustion Instability: Acoustic Interaction with a Burning Propellant Surface', J. Chem. Phys., Vol. 30, 1959, p. 1503.

7 Brid, J. F., Haar, L., Hart, R. W., and McClure, F. T., 'Effect of Solid Propellant Compressibility on Combustion Instability', J. Chem. Phys., Vol. 32, 1960, p. 1423.

8 Shinnar, R. and Dishon, M., 'Heat Transfer Stability Analysis of Solid Propellant Motors', in Solid Propellant Rocket Research, Academic Press, 1960, pp. 359.

9 Smith, A. G., 'A Theory of Oscillatory Burning of Solid Propellants Assuming a Constant Surface Temperature', ibid pp. 375.

10 Denison, R. M., Baum, E., 'A Simplified Model of Unstable Burning in Solid Propellants', ARS Journal, Vol. 31, No. 8, August 1961, p. 1112.

11 Bird, J. F., McClure, F. T., Hart, R. W., 'Acoustic Instability in the Transverse Modes of Solid Propellant Rockets', Applied Physics Laboratory Report TG-335-8, Johns Hopkins University, June 1961.

12 McClure, F. T., Hart, R. W., and Bird, J. F., 'Solid Propellant Rocket Motors as Acoustic Oscillators', Applied Physics Laboratory, Report TG-335-3, Johns Hopkins University, October 1959.

13 McClure, F. T., Hart, R. W., and Bird, J. F., 'On Acoustic Resonance in Solid Propellant Rockets', Applied Physics Laboratory Report TG-335-2, Johns Hopkins University, September 1959.

14 Thiokol Chemical Corporation, Elkton Division, 'A Proposal for a Program to Study Unstable Burning in Solid Propellants', EP106-59, September 25, 1959.

15 Technical Panel on Solid Propellant Combustion Instability, Applied Physics Laboratory, Johns Hopkins University, March 6-7, 1961.

16 Mawardi, O. K., 'Measurement of Acoustic Impedance', J.Ac. Soc. Am., 21, (March 1949), p. 84-91.

17 Grad, H., 'Resonance Burning in Rocket Motors', Communication on Pure and Applied Mathematics, Vol. 2, 1, 1949.

18 Smith, R. P., and Sprenger, P. F., 'Fourth Symposium on Combustion', p. 893-906, Williams and Wilkins, Balt. 1953.

19 Cheng, S. I., 'High Frequency Combustion Instability in Solid Propellant Rockets', Parts I and II, Jet Propulsion, 24, pp. 24, 102 (1954).

20 Moore, F. K., and Moslen, S. H., 'Transurse Oscillations in a Cylindrical Combustion Chamber', NASA, TN 3152, October (1954).

21 Aeronutronic Systems, Inc., 'Study of Detonation Behavior of Solid Propellants - Task No. 2, Resonance', Pub. No. C-271, September (1958) (Confidential).

22 Morse, P. M., 'Vibration and Sound', McGraw-Hill (1958), p. 367.

23 Crocco, L., and Cheng, S-1, 'Theory of Combustion Instability in Liquid Propellant Rocket Motors', Butterworth Sci. Pub. (1956).

24 Beranek, L. L., 'Acoustic Measurements', J. Wiley and Sons, 1949.

25 Morse, P. M., 'Vibration and Sound', McGraw-Hill, 2nd Ed., 1948.

26 Beranek, L. L., J. Ac. Soc. Am. 12, July 1940, pp. 14-23.

27 Mawardi, O. K., 'Measurement of Acoustic Impedance', ONR Tech. Memo. b, NR-014-903, May 25, 1949.

28 Price, E. W., 'Review of Combustion Instability in Solid Propellant Rockets', Manuscript, NOTS-5008/28 Feb. 1961 (Confidential).

DISTRIBUTION

Office of Naval Research
Propulsion Chemistry Branch (Code 426)
Department of the Navy
Washington 25, D. C.
Attn: Dr. Ralph Roberts
(2 copies)

Director, Advanced Research Projects Agency
The Pentagon
Washington 25, D. C.
Attn: Technical Information Officer
(6 copies)

Solid Propellant Information Agency
Applied Physics Laboratory
Johns Hopkins University
8621 Georgia Avenue
Silver Spring, Maryland
(3 copies)

Dr. F. T. McClure
Applied Physics Laboratory
The Johns Hopkins University
Silver Spring, Maryland

Dr. I. Silver
Department of the Navy
Bureau of Naval Weapons (RMMP-11)
Washington 25, D. C.

Special Projects Office
Department of the Navy
Washington 25, D. C.
Attn: LCDR R. L. Mcarthy

Naval Research Laboratory
Washington 25, D. C.
Attn: Dr. M. W. Oleson

Naval Ordnance Test Station
China Lake, California
Attn: Mr. E. W. Price

National Aeronautics and Space Admin.
1520 H Street
Washington 25, D. C.
Attn: Mr. E. Mitchell

National Aeronautics and Space Admin.
1520 H Street
Washington 25, D. C.
Attn: Mr. W. Cohen

Office of Aerospace Research
Department of the Air Force
Washington 25, D. C.
Attn: Mr. J. F. Masi

Ballistic Research Laboratories
Aberdeen Proving Ground
Maryland
Attn: Dr. L. A. Watermeier

Ballistic Research Laboratories
Aberdeen Proving Ground
Attn: Dr. J. H. Frazer

Allegany Ballistics Laboratory
Hercules Powder Company
Cumberland, Maryland
Attn: Mr. T. A. Angelus

Polytechnic Institute of Brooklyn
333 Jay Street
Brooklyn, New York
Attn: Professor R. D. Agosta

United Technology Corporation
P. O. Box 358
Sunnyvale, California
Attn: Dr. D. Altman

Grand Central Rocket Company
P. O. Box 111
Redlands, California
Attn: Dr. A. T. Camp

Office of Chief of Ordnance
Research and Development
Department of the Army
Washington 25, D. C.
Attn: Mr. J. A. Chalmers

Aerojet-General Corporation
Azusa, California
Attn: Dr. R. L. Lou

Aerojet-General Corporation
Azusa, California
Attn: Mr. R. F. Chaiken

Princeton University
James Forrestal Research Center
Princeton, New Jersey
Attn: Professor S. I. Cheng

Princeton University
James Forrestal Research Center
Princeton, New Jersey
Attn: Professor L. Crocco

Princeton University
James Forrestal Research Center
Princeton, New Jersey
Attn: Professor M. Summerfield

Princeton University
James Forrestal Research Center
Princeton, New Jersey
Attn: Professor J. Fenn

Harvard University
Department of Mechanical Engineering
Cambridge, Massachusetts
Attn: Professor H. W. Emmons

Chesapeake Instrument Company
Shadyside, Maryland
Attn: Mr. J. W. Fitzgerald

Atlantic Research Corporation
Alexandria, Virginia
Attn: Dr. R. Friedman

Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena 3, California
Attn: Dr. E. M. Landsbaum

Quantum Dynamics
19458 Ventura Boulevard
Tarzana, California
Attn: Dr. F. F. Liu

California Institute of Technology
Pasadena, California
Attn: Professor F. T. Marble

Cornell Aeronautical Laboratory
Buffalo, New York
Attn: Dr. G. Markstein

Lockheed Aircraft Corporation
Missile Systems Division
Sunnyvale, California
Attn: Dr. W. Nachbar

Stanford Research Institute
Menlo Park, California
Attn: Dr. P. L. Nichols

University of Utah
Salt Lake City, Utah
Attn: Professor N. W. Ryan

Rohm and Haas Company
Redstone Arsenal
Huntsville, Alabama
Attn: Dr. H. M. Shuey

Rocketdyne
6633 Canoga Avenue
Canoga Park, California
Attn: Dr. R. Thompson

Armour Research Foundation
10 West 35th Street
Chicago, Illinois
Attn: Dr. T. P. Torda

Aeronutronic
Propulsion Department
Newport Beach, California
Attn: Dr. L. Green, Jr.

Aeronutronic
Propulsion Department
Newport Beach, California
Attn: Dr. H. Shanfield

Purdue University
Lafayette, Indiana
Attn: Professor M. J. Zucrow

Thiokol Chemical Corporation
Redstone Arsenal
Huntsville, Alabama
Attn: Dr. R. H. Wall

Thiokol Chemical Corporation
Reaction Motors Division
Denville, New Jersey
Attn: Dr. H. G. Wolfhard

Director of Research
AeroChem Research Laboratories, Inc.
Princeton, New Jersey
Attn: Dr. H. F. Calcote